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13. ABSTRACT (*Maximum 200 words*)

This program involved research on the utilization of near field optical microscopic and spectroscopic techniques to investigate spatial configurations on a nanometer scale of both integrated photonic structures and semiconductor nanostructures. We have made significant accomplishments in our research effort involving use of these near field techniques to investigate several important areas including photonic bandgap structures or photonic crystals, vertical cavity surface emitting lasers (VCSEL's), and optical waveguides including multiple interference structures. Near field microscopic and spectroscopic measurements performed on these structures provides more understanding of their behavior than can be ascertained in other ways; such understanding is expected to point toward improved device structures.

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(1) List of Publications and Conference Presentations

J. Kim, J.T. Boyd, H.E. Jackson, and K.D. Choquette "Near Field Spectroscopy of Selectively Oxidized Vertical Cavity Surface Emitting Lasers," Applied Physics Letters, Vol. 76, pp. 526-528, 31 Jan., 2000.

Jeongyong Kim, Dave E. Pride, Joseph T. Boyd, and Howard E. Jackson, "Spectrally-Resolved Near Field Investigation of Proton Implanted Vertical Cavity Surface Emitting Lasers," Applied Physics Letters, Vol. 72, pp. 3112-3114, 1998.

D.H. Naghski, J.T. Boyd, H.E. Jackson, and A.J. Steckl, "Potential for Size Reduction of AlGaAs Optical Channel Waveguide Structures Fabricated by Focused Ion Beam Implantation and Oxidation," Optics Communications, Vol. 150, pp. 97-100, 1 May, 1998.

J.Y. Kim, D. E. Pride, J.T. Boyd, and H. E. Jackson, "Spectroscopic NSOM of VCSELs," presented at and published in the proceedings of the 24rd International Conference on the Physics of Semiconductors (ICPS-24), Jerusalem, Israel, 1998.

A. Sharma, J. Yarrison-Rice, H.E. Jackson, D. Naghski, and J. T. Boyd "NSOM Characterization of photonic bandgap structures,"presented at the Symposium on Nano-, Micro-, and Mesoscale Technologies in Science and Engineering, University of Cincinnati, 1999.

J. Yarrison-Rice, P. Swarup, P. R. Rice, A. Sharma, H. Jackson, D. Naghski, J. T. Boyd, M. Charlton, and G. J. Parker "Near field experiments and theoretical modeling on visible photonic bandgap structures," presented at 1999 CLEO/QELS Conference.

J. M. Yarrison-Rice, A. Sharma, D. Naghski, J. T. Boyd, H. E. Jackson, and M. Charlton, "Near Field Scanning Optical Microscopy Investigation of Visible Photonic Band Gap Device," presented at the American Physical Society Centenial Meeting, March 1999.

S. M. Lindsay, D. H. Naghski, J. T. Boyd, and H. E. Jackson, "NSOM Probe of Multimode Interference at 1.06 μm in Complex Optical Waveguide Structures," *Bull. Am. Phys. Soc.* **43**, 482 (1998).

(2) Scientific Personnel

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(3) Inventions None

(4) Scientific Progress and Accomplishments

This research program has involved research on the utilization of near field scanning optical microscopic (NSOM) and spectroscopic techniques to investigate spatial configurations on a nanometer scale of both integrated photonic structures and semiconductor nanostructures. We have made significant accomplishments in our research effort involving use of these near field techniques to investigate several important areas including photonic bandgap structures or photonic crystals, vertical cavity surface emitting lasers (VCSEL's), and photonic waveguides including multiple interference structures. Near field microscopic and spectroscopic measurements performed on these structures provides more understanding of their behavior than can be ascertained in other ways; such understanding is expected to point toward improved device structures.

In what follows some significant accomplishments in our research effort involving a NSOM investigation of several important areas including photonic bandgap structures or photonic crystals, vertical cavity surface emitting lasers (VCSEL's), and photonic waveguides.

(a) Near field spectroscopy of 10 μm aperture selectively oxidized VCSEL's

We have studied selectively oxidized vertical-cavity surface-emitting lasers (VCSELs) by spectrally resolved near field scanning optical microscopy. In particular, we have been characterizing 10 μm aperture VCSELs which display a complex transverse mode structure compared to slightly smaller aperture samples. We have obtained spatially and spectrally resolved images of both subthreshold emission and lasing emission near the 850 nm wavelength region and have carried out an analysis of these images.

Below threshold, spatially localized high gain regions, which emit intensity maxima within the active area, are observed. In Figure 1 below we display a near field image of total integrated intensity at a current of 3.3 ma, just below the threshold current for this sample. The selectively oxidized apertures are reflected in the boundaries of the image and are square in shape as expected from the symmetry of the AlAs layer which is oxidized. One also observes that there are local regions of efficient. These were found to serve as lasing centers just above threshold. Above threshold, the near field spatial modal distributions of low-order transverse modes are being identified by spectrally analyzing the emission; these were found to be complex and somewhat different from those measured in the far field.

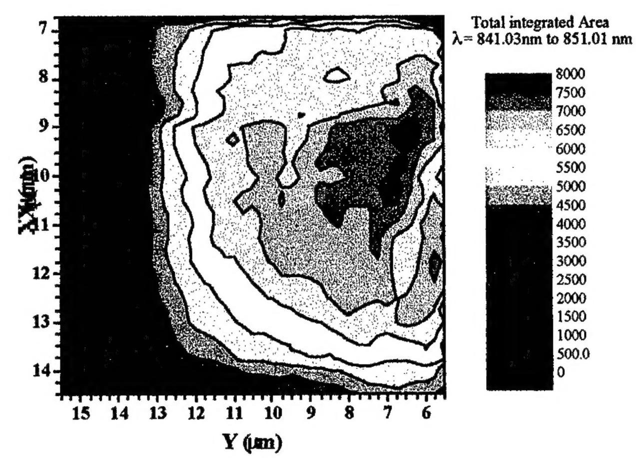

Figure 1: 2D near field scan of total integrated intensity of all modes as a function of position on the VCSEL.

Experimentally, each of the near field images is obtained spectroscopically. This means that at any specific position of the VCSEL one can obtain a spectra of all the modes that are emitting at that location. In Figure 2a,b,c below we show representative spectra obtained near

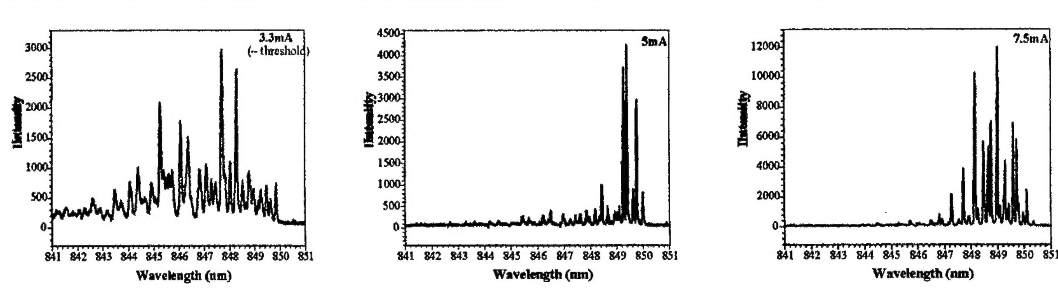

Figure 2: Near field spectra of 10 μm VCSEL at a) 3.3 mA, b) 5 mA, and c) 7.5 mA.

the center of the VCSEL at currents of 3.3 ma (just below threshold), 5 ma, and 7.5 ma. The spectra are clearly different both in structure and in wavelength response as the current increases. For instance, the 3.3 mA data exhibits a broad background florescence underlying the sharp emission peaks that are beginning to form; this florescence is insignificant in comparison to the emission modes once the VCSEL is lasing (above 3.5 mA). Recall that a given resonant mode moves to longer wavelength with increasing current because of the increase in refractive index with temperature; this is also reflected in the above three spectra . We have measured this increase for several modes and find the shift in peak position with current is 0.145 nm/mA.

In order to view the spatial distribution of the transverse modes, one can choose a specific wavelength and map its intensity across the VCSEL aperture. We observe that the emission patterns, at both below and above threshold currents, exhibit higher order structure with decreasing wavelength. In the 5 mA scans for instance, we see the 849.94 nm mode is spatially

Transverse Modes at 5 mA in 10 μm VCSEL

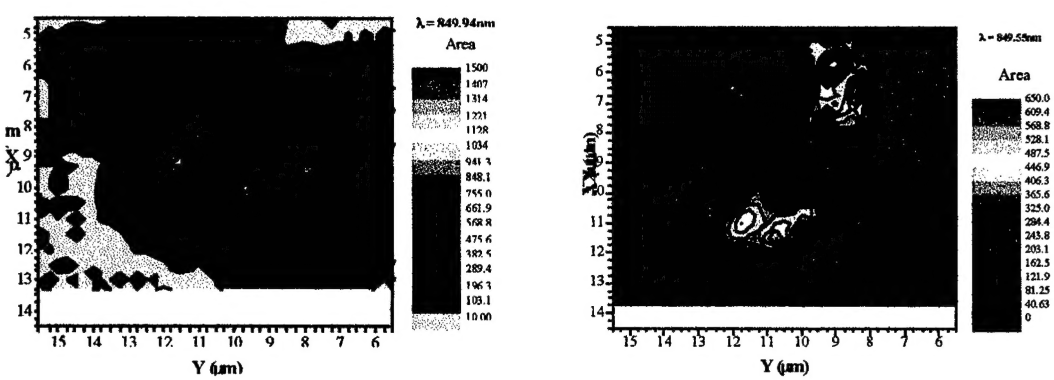

Figure 3: Near field image of a) lowest order mode at 849.94 nm and b) third order mode at 849.55 nm.

localized near the center of the VCSEL with 3 intense peaks within a single elliptically shaped lobe (see Figure 3a). This mode is the lowest order mode we observe. In the far field, that is

after diffraction effects have taken place, we find that the mode is more evenly distributed into a single elliptical mode with a central intensity maximum.

In contrast, the near field scan of the 849.55 nm mode in Figure 3b has a larger spatial extent, spreading further across the aperture and exhibiting a more complex structure with several individual high intensity lobes evident.

As we move to the far field, about 10 μm above the surface of the VCSEL, we observe in the spectroscopic image of the 849.55 nm mode (Figure 4) bright emissions seen in the near field scan remain distinctly separated in the far field indicating a higher order mode being established. Note the smoother intensity distribution.

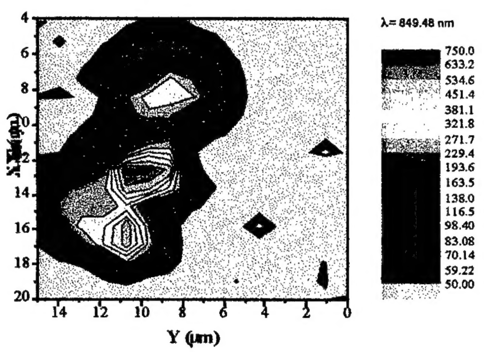

Figure 4: Far field image of third order mode (same mode as Figure 3b above) at 849.55 nm.

Similar results are observed at all currents; namely a large number of modes are evident in the spectra with higher order modes occurring as one moves lower in wavelength. The higher the order of the mode the more of the VCSELs gain media is utilized resulting in modes with a larger cross sectional area. These modes have very complex intensity patterns in the near field which generate a smoother far field distribution as the light propagates away from the surface of the VCSEL. Of interest for the future is a measurement of the polarization of these modes.

In summary, we have obtained both near field and far field data of both spectrally and spatially resolved images for selectively oxidized 10 μm square aperture VCSELs using the NSOM technique. The VCSEL's subthreshold behavior exhibiting spatially non-uniform florescence, and the lasing behavior exhibiting gain narrowing were characterized. The spectra

of these square aperture devices are rich with many higher order modes emitted at all currents above threshold. Individual transverse modes were identified and their spatial distributions were mapped as a function of input current. The near field data provide a unique spatially local information on the emission characteristics of these selectively oxidized vertical cavity surface emitting lasers.

(b) NSOM Measurements in Optical Waveguides

An important aspect of this ARO-supported research is the first reported near field measurements of a semiconductor channel waveguide[1]. NSOM measurements have been performed on single mode AlGaAs ridge channel waveguides by endfire coupling light of 830 nm from a semiconductor laser into the channel waveguide. The optical intensity distribution just above the surface of the waveguide structure has been measured by scanning a tapered fiber probe transverse to the waveguide propagation direction. An accurate description of submicron features in the intensity profile near the ridge edges, as well as the magnitude of the field outside the channel, requires the use of beam propagation method (BPM) techniques. Our commercial BPM capability includes commercial FDTD software, resulting in a powerful capability for light propagating in waveguide structures, including photonic bandgap structures.

Although we made some significant accomplishments with photonic waveguides, we were unable to achieve one of our goals, that is, performing waveguide measurements which will allow use of NSOM to measure for the first time standing wave patterns existing within optical waveguides. Since the separation between nulls in these patterns is one-half wavelength inside the material, NSOM is one of the few if not the only practical way of performing such measurements. Achieving success in these measurements will provide a valuable technique for

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[1] C.D. Poweleit, D.H. Naghski, S.M. Lindsay, J.T. Boyd, and H.E. Jackson, "Near Field Scanning Optical Measurements of Optical Intensity Distributions in Semiconductor Channel Waveguides," Applied Physics Letters, Vol. 69, pp. 3471-3473, 1996.

experimentally characterizing waveguide reflector structures, including distributed grating reflectors, and provide quantitative verification of NSOM sub-wavelength resolution. Distributed grating reflectors, or distributed Bragg reflectors which provide precision wavelength response, are being increasingly utilized in wavelength division multiplexing systems (WDM). We did fabricate optical waveguide structures utilizing silicon oxynitride technology that include both metal reflectors, fabricated by e-beam evaporation and liftoff, and grating reflectors, fabricated by focused ion beam processing. We may yet succeed in making these measurements and if so, we will acknowledge ARO support.

(5) Technology Transfer

Interaction with Army Research Laboratory

Near field measurements have been carried out on a multimode interference device, fabricated and supplied by ARL, that uses multimode interference to send light from one optical channel waveguide to four different output channel waveguides. Near field interference patterns were observed over large (60 μm x 20 μm) areas and detailed modeling of the structure using beam propagation methods was carried out.